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GlueX CITATIONS PERIMENT

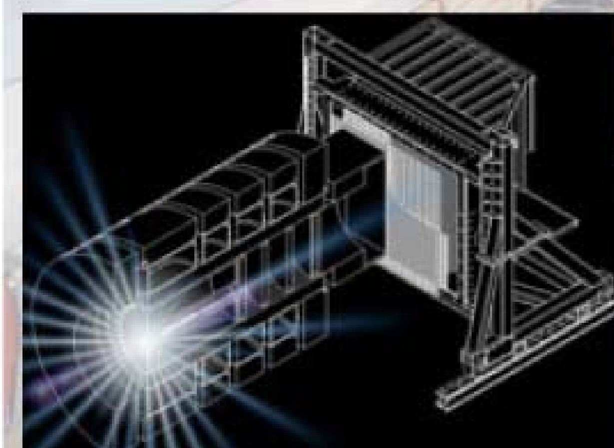
Hall D at Jefferson Lab

Science of Quark Confinement

and Meson Spectroscopy

Presentation to PAC23

January 17, 2003



Alex R. Dzierba
Indiana University

representing the GlueX Collaboration

100 Physicists (including 16 theorists) from 6 countries including 10 states + D. of C.

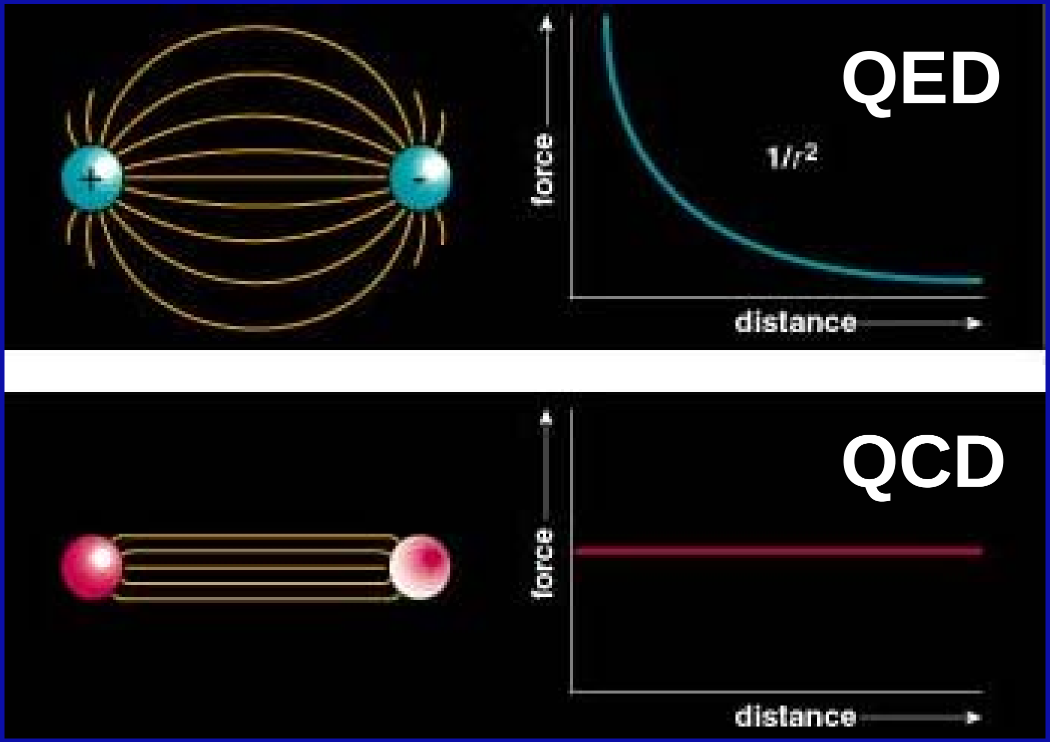
- Australia
- Canada
- Poland
- Russia
- Scotland
- USA

Connecticut, D.C., Florida, Indiana, New York, New Mexico, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia

Science of Confinement

- The spectroscopy of light mesons led to the quark model and QCD: mesons are quark-antiquark color singlet bound states held together by gluons.

- The gluons of QCD carry color charge and interact strongly (in contrast to the photons of QED).



Bound states involving gluons should exist – but solid experimental evidence is lacking.

Science of Confinement

- **The gluons are thought to form flux tubes which are responsible for confinement – flux tubes are predicted by both models and lattice QCD.**

- **The excitations of these flux tubes give rise to new hybrid mesons and their spectroscopy will provide the essential experimental data that will lead to an understanding of the confinement mechanism of QCD.**

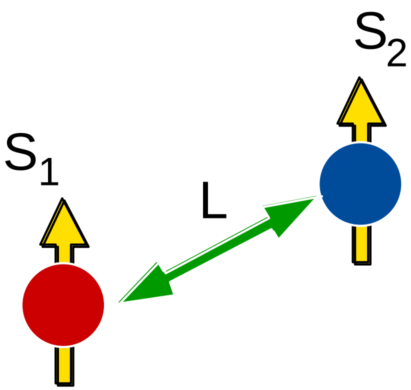
- **A subset of these mesons - *exotic hybrid mesons* - have unique experimental signatures. Their spectrum has not yet been uncovered but there is strong reason to believe that photons are the ideal probe to map out the spectrum of this new form of matter.**

This is the goal of the GlueX Experiment

Normal Mesons – $q\bar{q}$ color singlet bound states

Spin/angular momentum configurations & radial excitations generate our known spectrum of light quark mesons.

Starting with u - d - s we expect to find mesons grouped in nonets - each characterized by a given J, P and C.

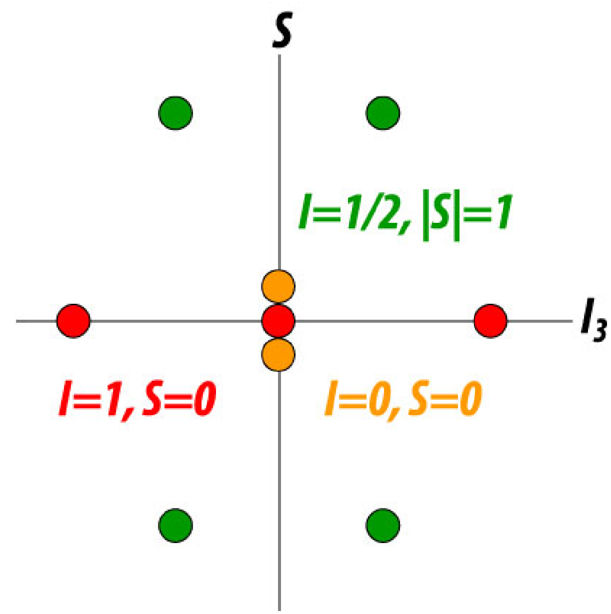


$$S = S_1 + S_2$$

$$J = L + S$$

$$P = (-1)^{L+1}$$

$$C = (-1)^{L+S}$$



$$J^{PC} = 0^{-+}\ \ 0^{++}\ \ 1^{--}\ \ 1^{+-}\ \ 2^{++}\ \ldots$$

Allowed combinations

$$J^{PC} = 0^{--}\ \ 0^{+-}\ \ 1^{-+}\ \ 2^{+-}\ \ldots$$

Not-allowed: exotic

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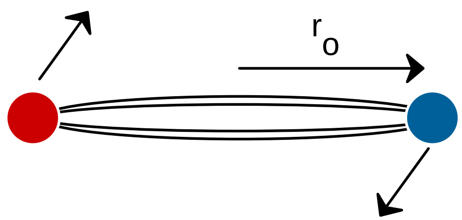
Early Notion of Flux Tubes

In the 1970's Nambu points out that linear Regge trajectories imply that quarks inside are tied by strings.



$$\frac{v}{c} = \frac{r}{r_o}$$

energy:

$$\boxed{E = mc^2 = 2\int_0^{r_o} \frac{k \cdot dr}{\sqrt{1 - v^2 / c^2}} = k r_o \pi}$$

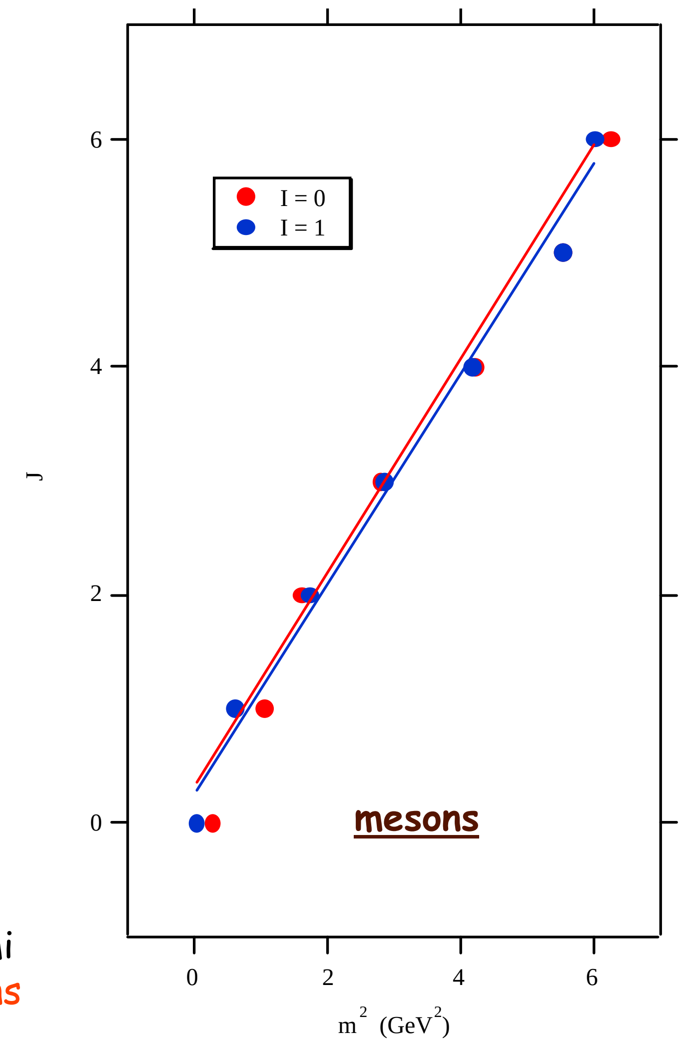
angular momentum:

$$\boxed{J = \frac{2}{hc^2} \int_0^{r_o} \frac{kvr \cdot dr}{\sqrt{1 - v^2 / c^2}} = \frac{k r_o^2 \pi}{2hc}}$$

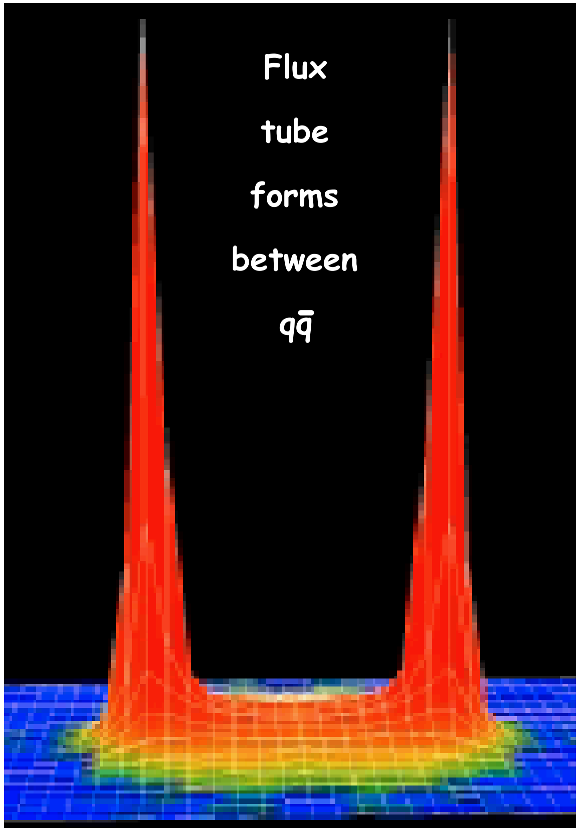
k = constant energy density per length
implies a linear potential: V = kr

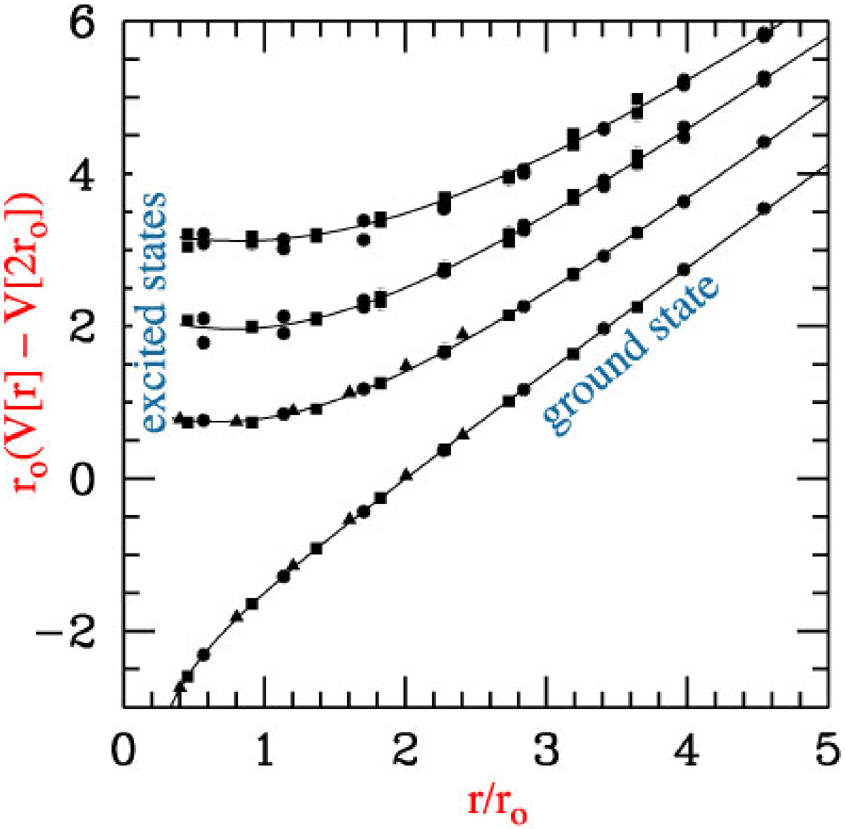
$$\boxed{J \propto m^2}$$

k = 1 GeV/fermi
or about 16 Tons



Early Lattice Calculations Also Predict Flux Tubes

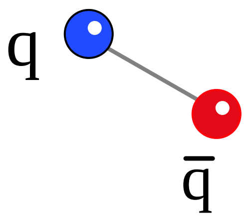




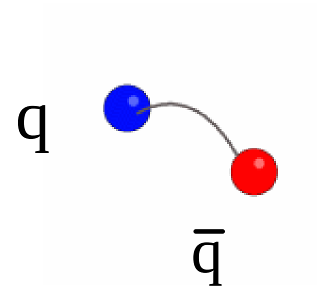
From G. Bali: quenched QCD with heavy quarks

Exciting the Flux Tube

Normal meson:
flux tube in ground state



Excite the flux tube:



There are two degenerate first-excited transverse modes with J=1
– clockwise and counter-clockwise –
and their linear combinations lead to $J^{PC} = 1^{-+}$ or $J^{PC}=1^{+-}$ for the excited flux-tube

Quantum Numbers for Hybrid Mesons

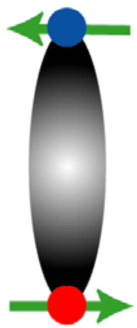
Quarks $\oplus$ **Excited Flux Tube** → **Hybrid Meson**

$S = 0$

$L = 0$

$J^{PC} = 0^{-+}$

like π, K



$$J^{PC} = \begin{cases} 1^{+-} \\ 1^{-+} \end{cases}$$

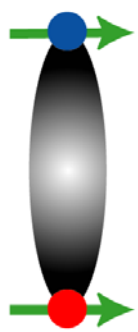
$$J^{PC} = \begin{cases} 1^{--} \\ 1^{++} \end{cases}$$

$S = 1$

$L = 0$

$J^{PC} = 1^{--}$

like γ, ρ



$$J^{PC} = \begin{cases} 1^{+-} \\ 1^{-+} \end{cases}$$

Exotic

$$J^{PC} = \begin{cases} 0^{-+} \quad 1^{-+} \quad 2^{-+} \\ 0^{+-} \quad 1^{+-} \quad 2^{+-} \end{cases}$$

So only parallel quark spins lead to exotic J^{PC}

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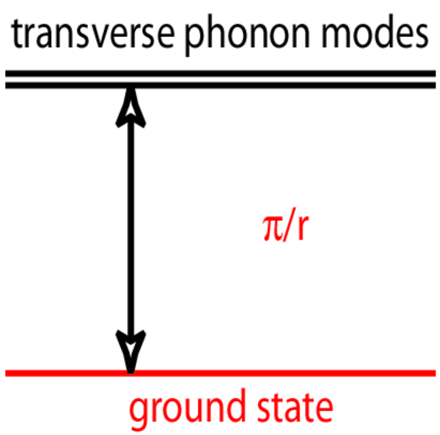
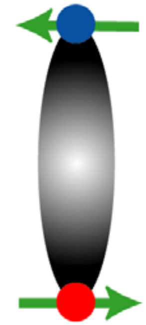
Hybrid Mesons



Hybrid mesons



1 GeV/c^2 mass difference (π/r)

Normal mesons

Hybrid Masses

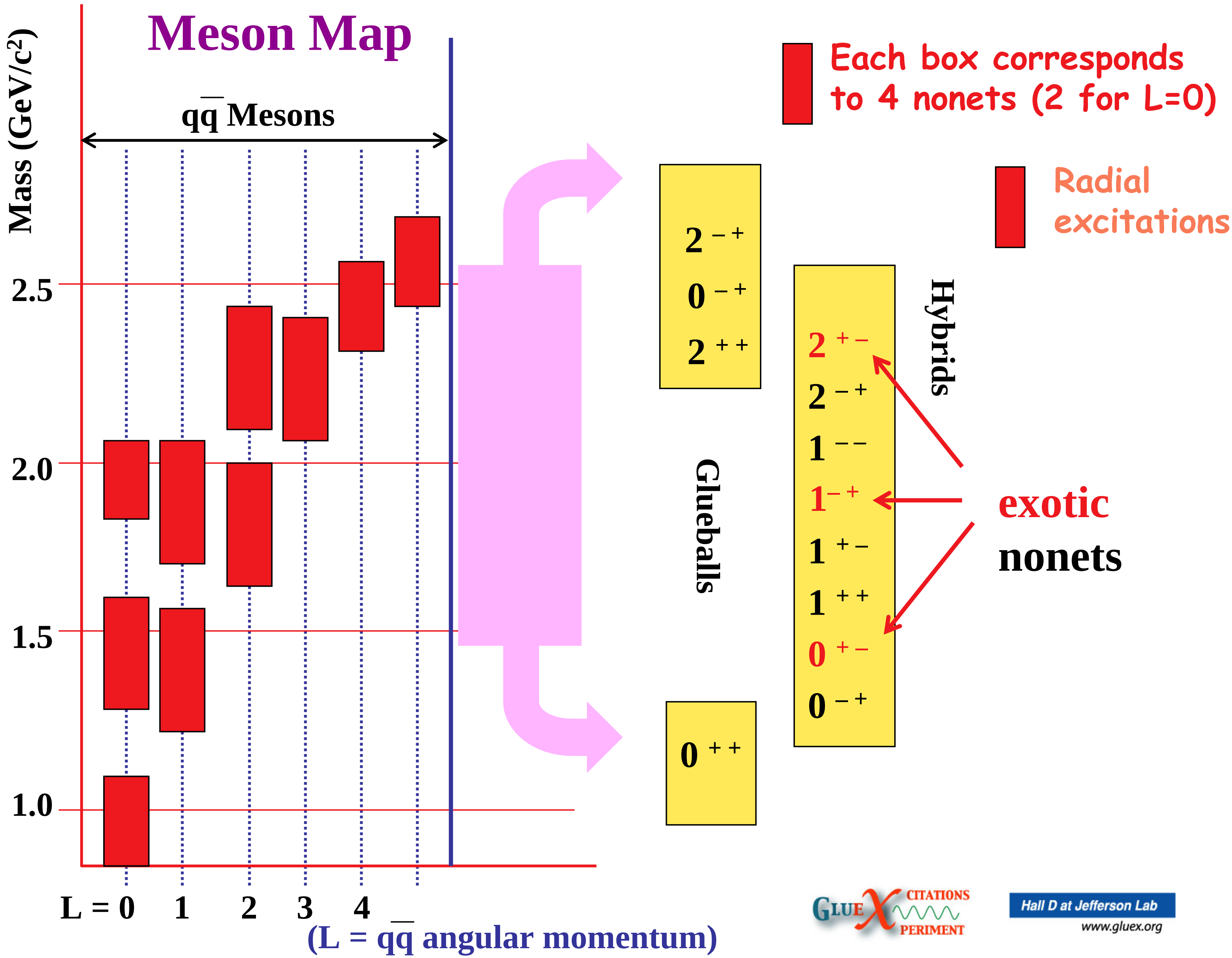
Lattice calculations --- 1^{-+} nonet is the lightest

UKQCD (97)	1.87 ±0.20
MILC (97)	1.97 ±0.30
MILC (99)	2.11 ±0.10
Lacock(99)	1.90 ±0.20
Mei(02)	2.01 ±0.10

~2.0 GeV/c^2

$\left.\begin{array}{l}1^{-+}\\0^{+-}\end{array}\right\}$ Splitting ≈ 0.20

2^{+-}



Meson Map
Mass (GeV/c²)
q$\bar{q}$ Mesons
Each box corresponds to 4 nonets (2 for L=0)
Radial excitations
2.5
2.0
1.5
1.0
2^{-+}
0^{-+}
2^{++}
Glueballs
0^{++}
Hybrids
2^{+-}
2^{-+}
1^{--}
1^{-+}
1^{+-}
1^{++}
0^{+-}
0^{-+}
exotic
nonets
L = 0 1 2 3 4
(L = q$\bar{q}$ angular momentum)
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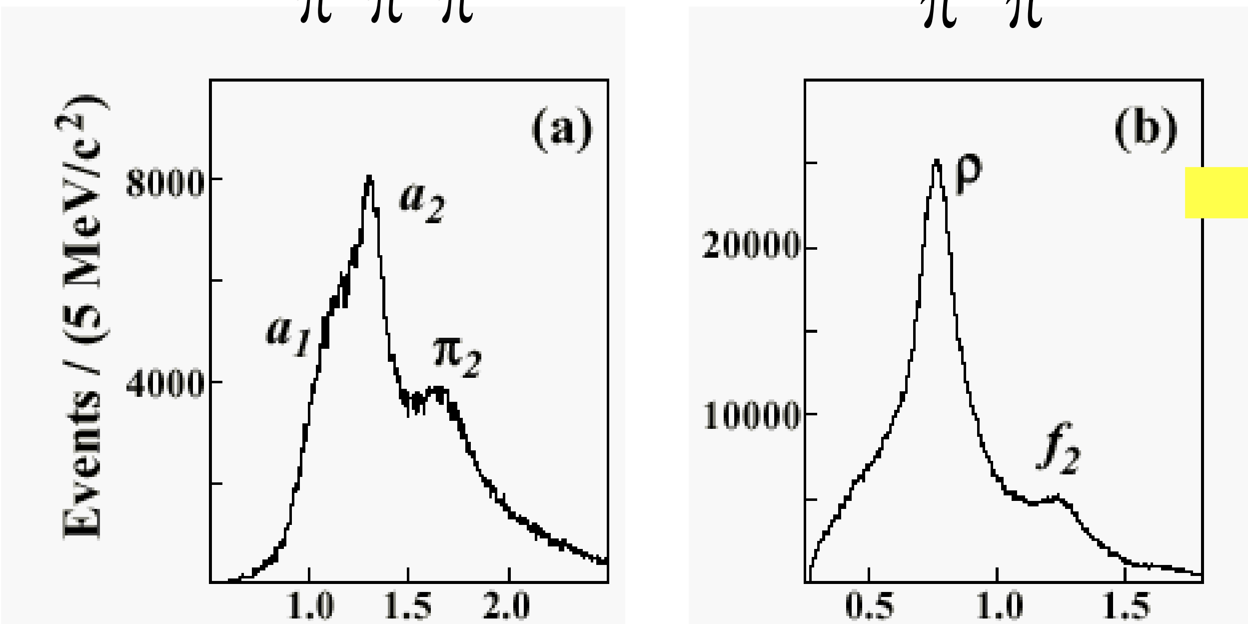
First Evidence for an Exotic Hybrid from E852

$$\pi^- p \rightarrow \pi^+ \pi^- \pi^- p$$

At 18 GeV/c

$\pi^+\pi^-\pi^-$ $\qquad$ $\pi^+\pi^-$



$M(\pi^+\pi^-\pi^-)\ \left[\mathrm{GeV}/c^2\right]$ $\qquad$ $M(\pi^+\pi^-)\ \left[\mathrm{GeV}/c^2\right]$

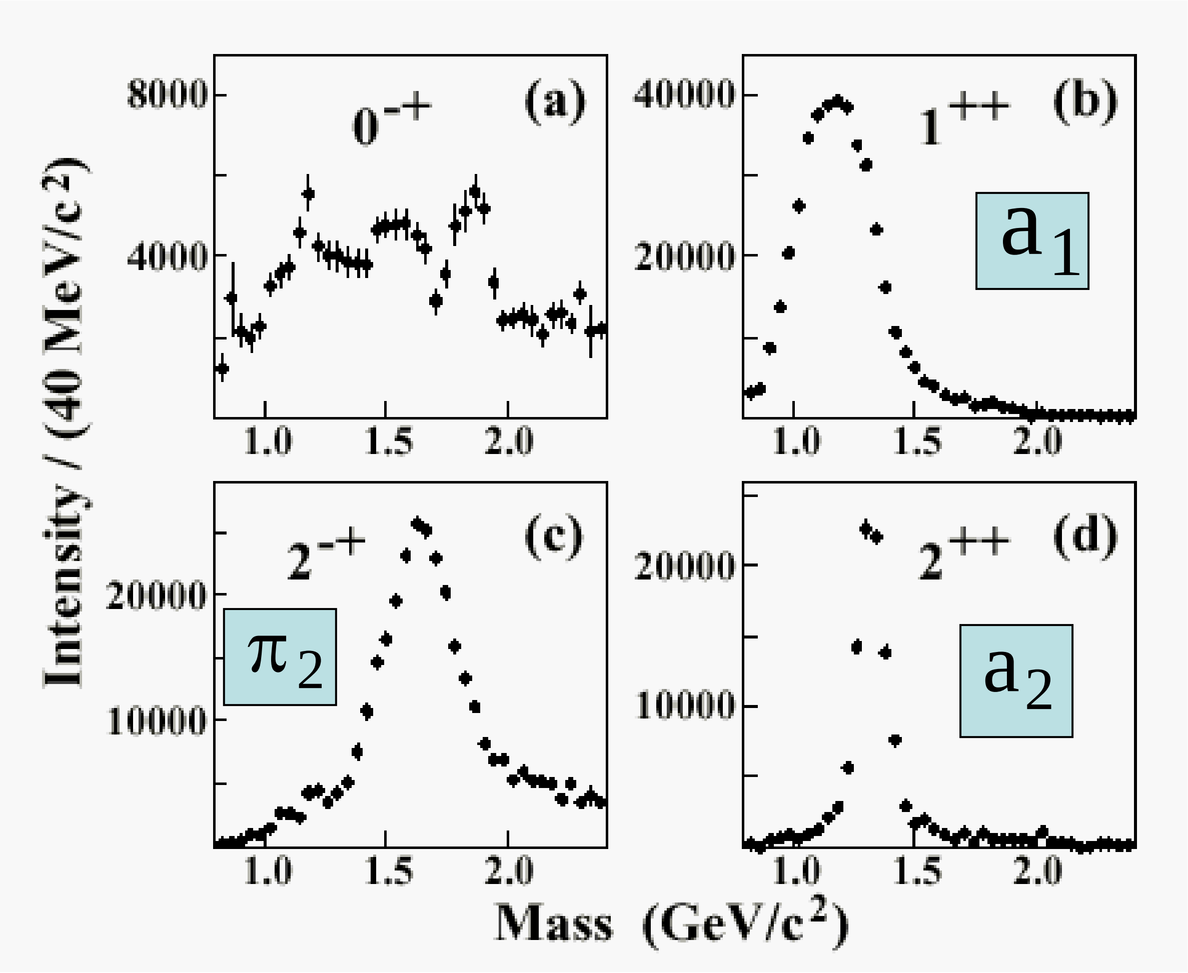
suggests

$$\pi^- p \rightarrow \rho^0 \pi^- p$$
$$\rightarrow \pi^+ \pi^- \pi^- p$$

dominates

to partial wave analysis (PWA)

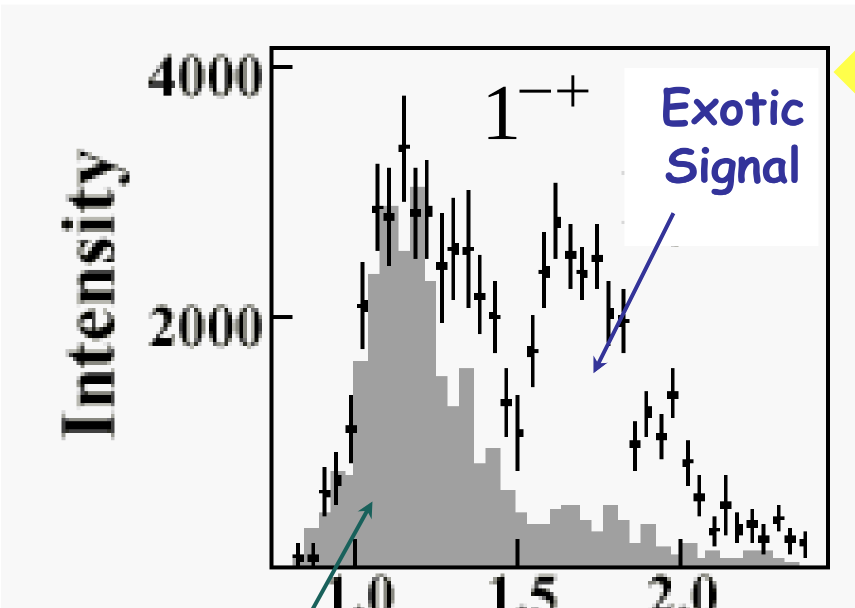
Results of Partial Wave Analysis



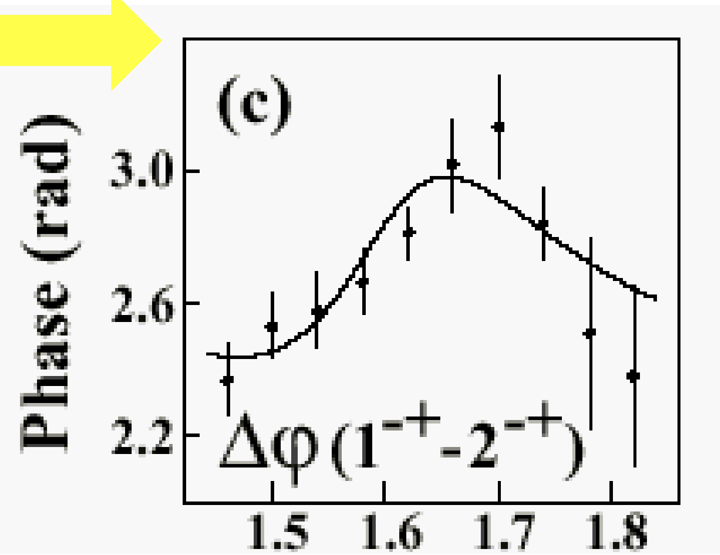
Benchmark resonances

An Exotic Signal in E852

Correlation of Phase & Intensity



Exotic Signal

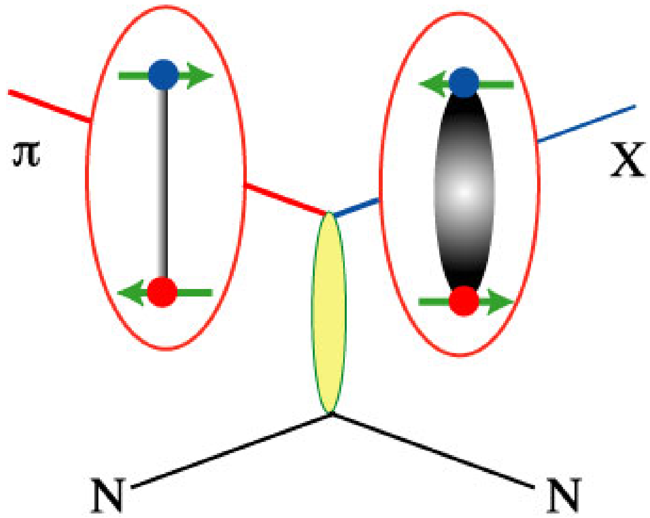


$M(\pi^+\pi^-\pi^-)\ \left[\mathrm{GeV}/c^2\right]$

Leakage From Non-exotic Wave

due to imperfectly understood acceptance

Experiment E852 Used π Probes

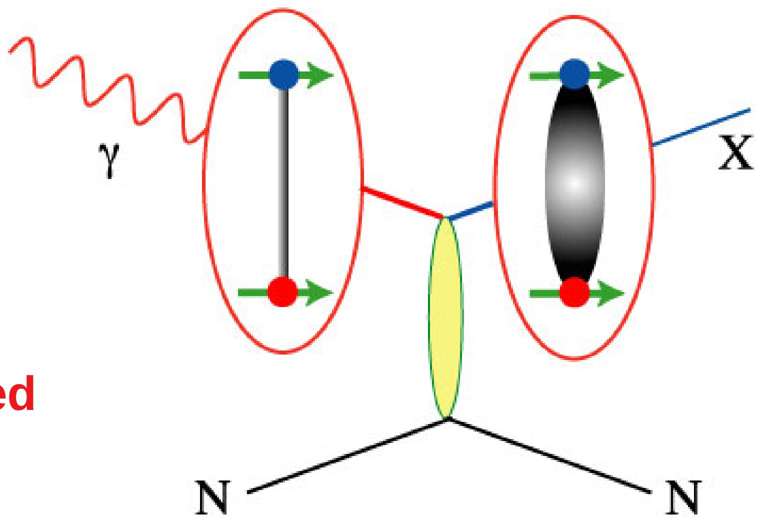


Quark spins
anti-aligned

Exotic hybrids
suppressed

Extensive search with some evidence
but a tiny part of the signal

Exotic Hybrids Will Be Found More Easily in Photoproduction



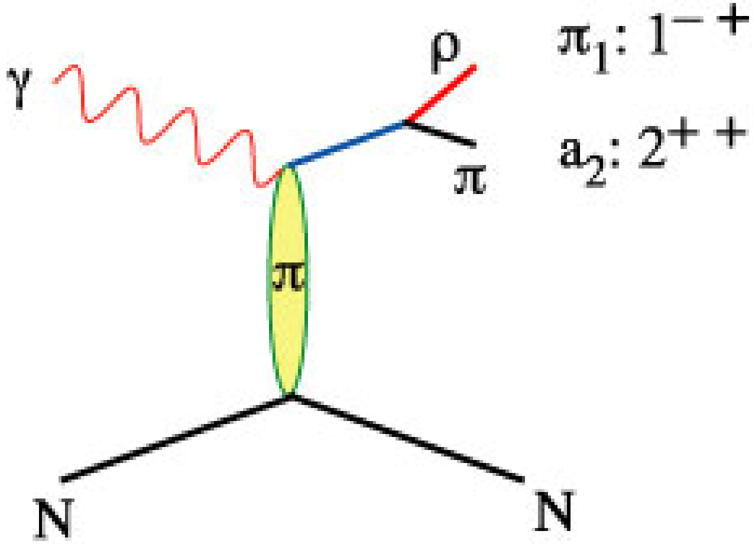
Quark spins
already aligned

Production of exotic
hybrids favored.
Almost no data available

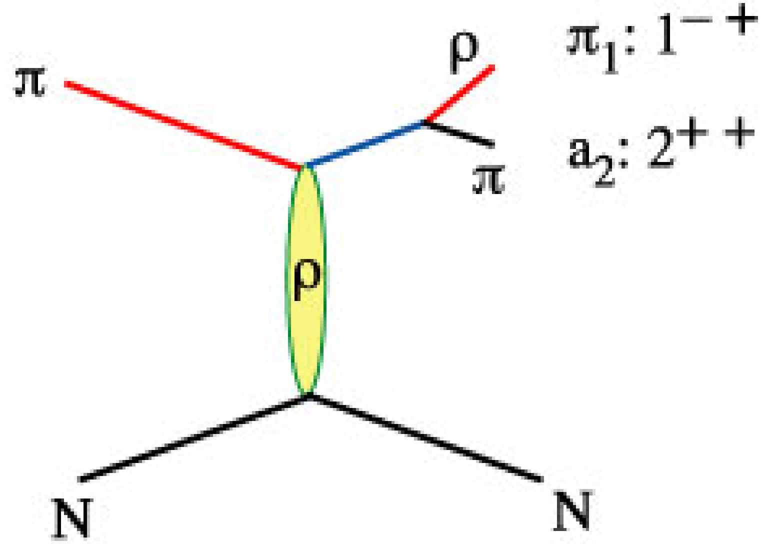
There are strong indications from theory that photons will produce exotic hybrid mesons with relatively large cross sections.

Comparing

Szczepaniak and Swat



$$\frac{\pi_1}{a_2} \approx 0.5 - 1.0$$



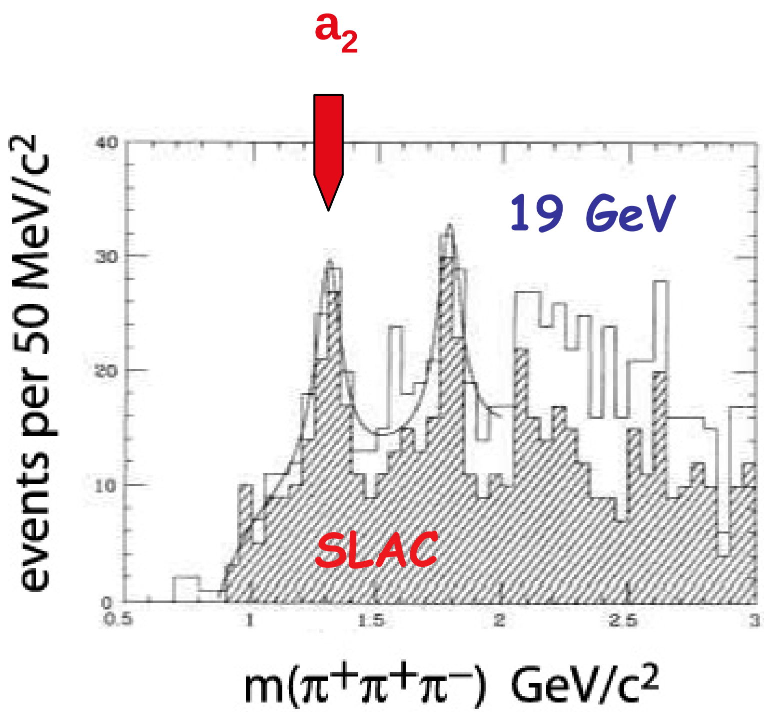
$$\frac{\pi_1}{a_2} \approx 0.05$$

Due to:

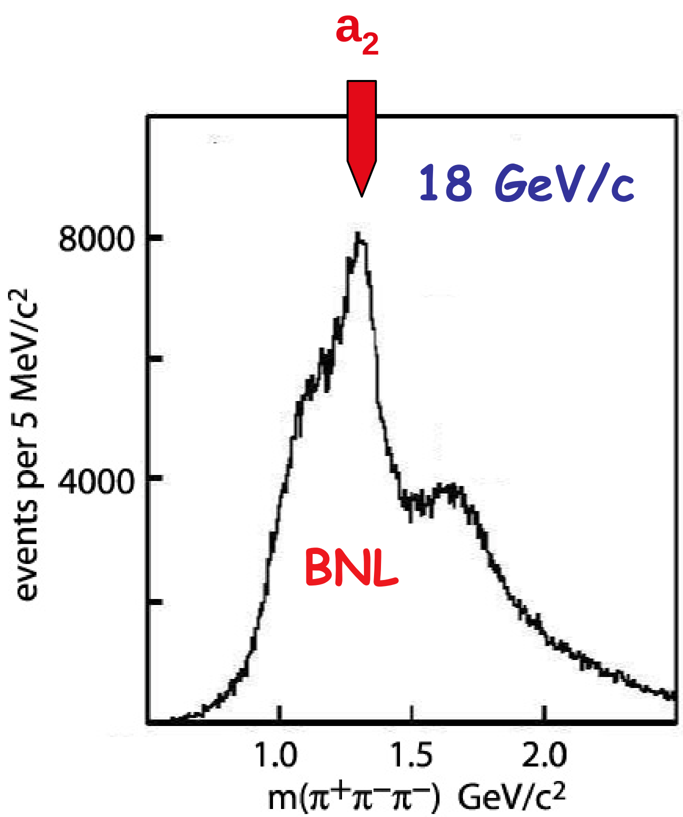
- Coupling at both vertices
- t-dependence of exchanges

Photoproduction and Pion Data

We will use for comparison – the yields for production of the well-established and understood a_2 meson



$$\gamma p \rightarrow \pi^+ \pi^+ \pi^- n$$



$$\pi^- p \rightarrow \pi^+ \pi^- \pi^- p$$

Hybrid Candidates?

In all E852 sightings the P-wave is small compared to a2. For CB P-wave and a2 similar in strength

$\pi^- p \to \rho^0 \pi^- p$

$$M = 1593 \pm 8^{+29}_{-47} \;\; \mathrm{MeV}/c^2$$
$$\Gamma = 168 \pm 20^{+150}_{-12} \;\; \mathrm{MeV}/c^2$$

Confirmed by VES
More E852 3π data to be analyzed

$\pi^- p \to \eta \pi^- p$

$$M = 1370 \pm 16^{+50}_{-30} \;\; \mathrm{MeV}/c^2$$
$$\Gamma = 385 \pm 40^{+65}_{-105} \;\; \mathrm{MeV}/c^2$$

Confirmed by Crystal Barrel similar mass, width

$\pi^- p \to \eta' \pi^- p$

$$M = 1597 \pm 10^{+45}_{-10} \;\; \mathrm{MeV}/c^2$$
$$\Gamma = 340 \pm 40^{+50}_{-50} \;\; \mathrm{MeV}/c^2$$

Being re-analyzed

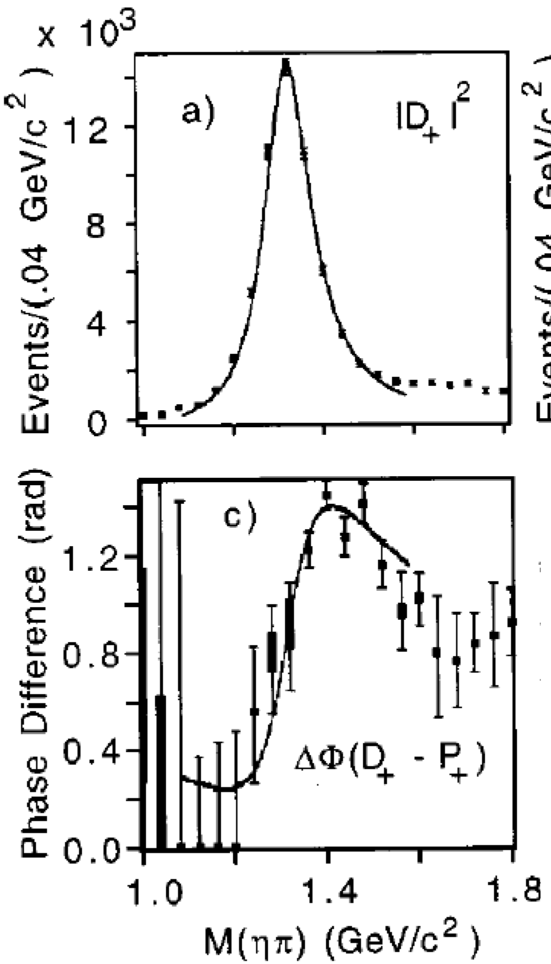
$\pi^- p \to \eta \pi^0 n$

New results: No consistent B-W resonance interpretation for the P-wave

E852 Experiment at BNL

$\pi^- p \rightarrow \eta \pi^- p$

After PWA:

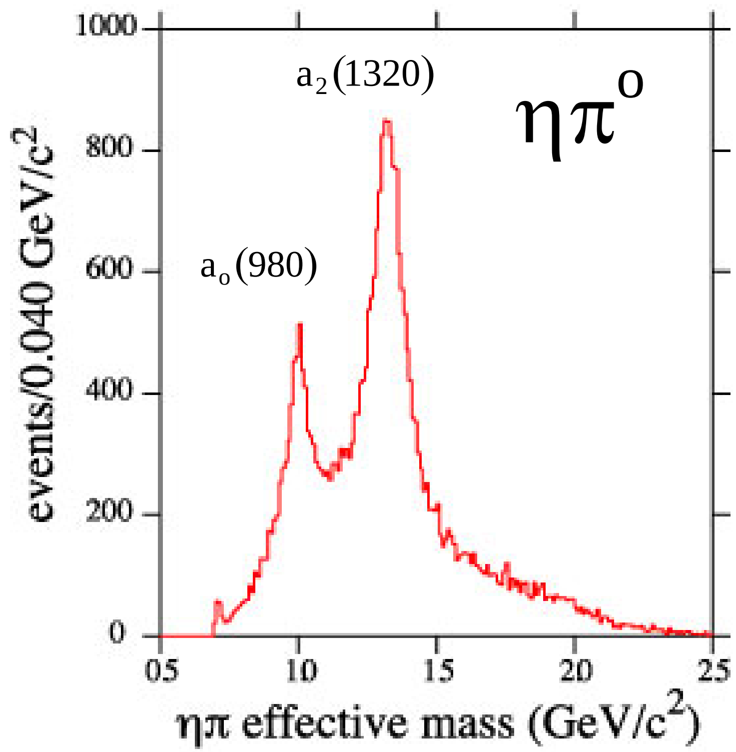


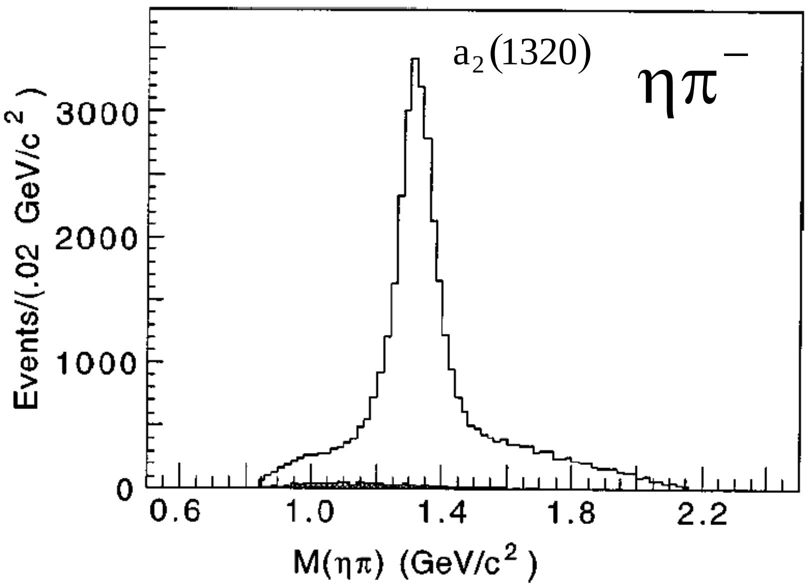
Conclusion: an exotic signal at a mass of 1400 MeV and width of about 385 MeV

Neutral $\eta\pi$

Neutral vs charged production:

- ✓ *C* is a good quantum number
- ✓ a_o and a_2 are produced (helps with ambiguities)
- ✓ only one detector involved





Neutral $\eta\pi$

Angular distributions fitted to obtain PWA fits - mathematical ambiguities present

Moments of spherical harmonics also fitted - these are not ambiguous

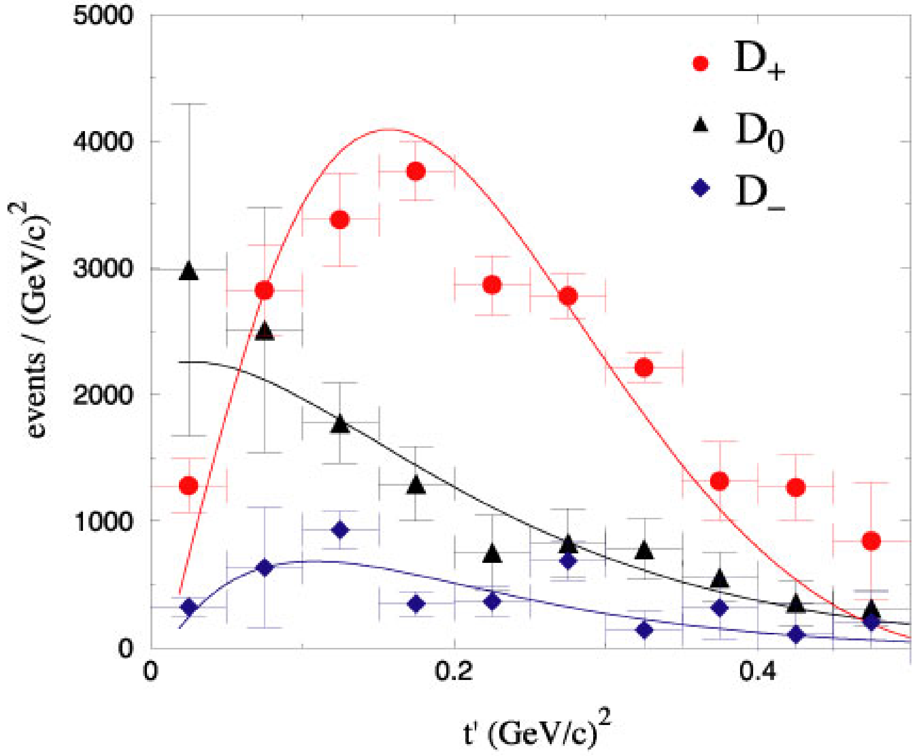
Waves included:

S_0

P_+ P_0 P_-

D_+ D_0 D_-

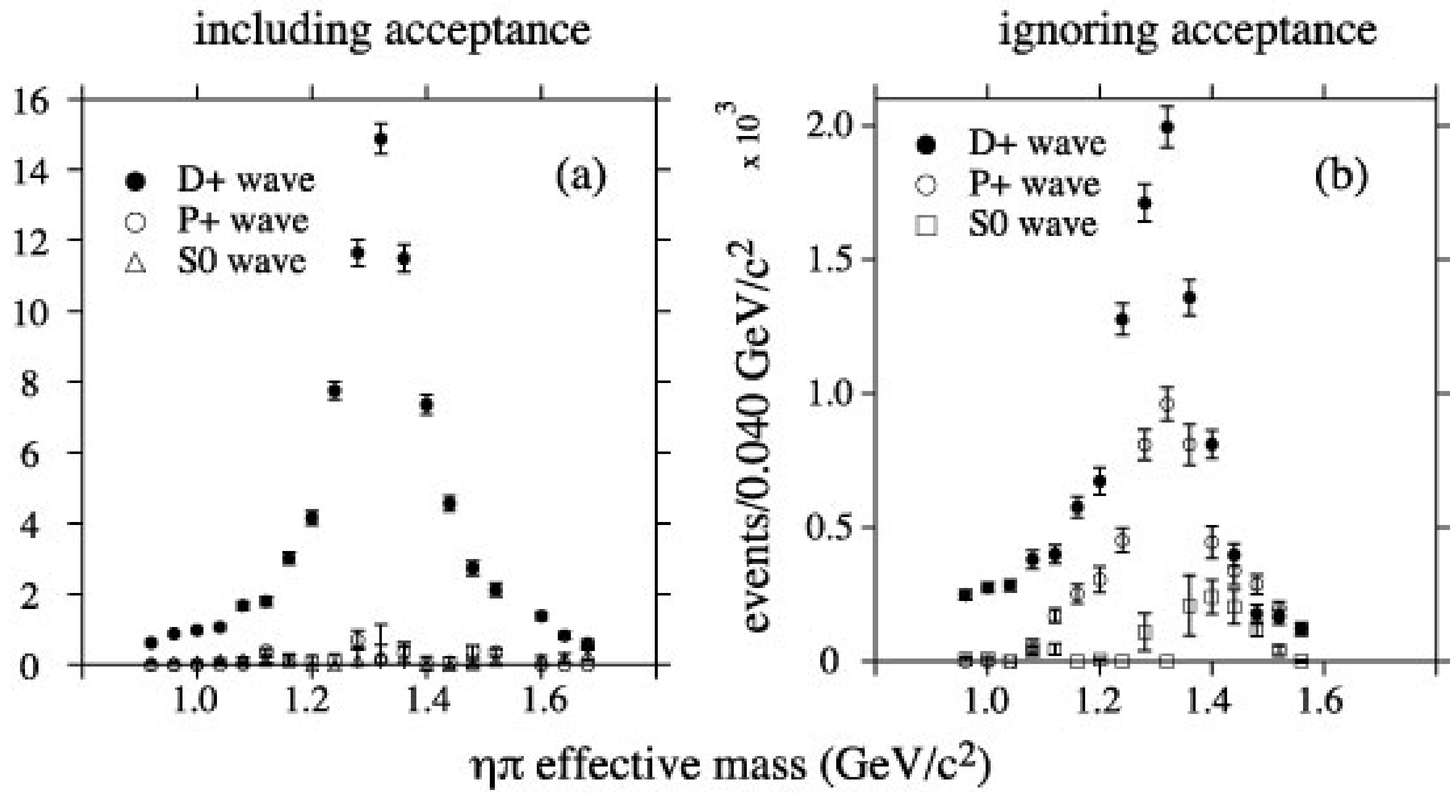
Details of D-wave solutions:



Conclusion: A P-wave is present but there is no consistent BW-resonance behavior but it consistent with final state interactions.

Leakage Studies

Monte Carlo studies - E852



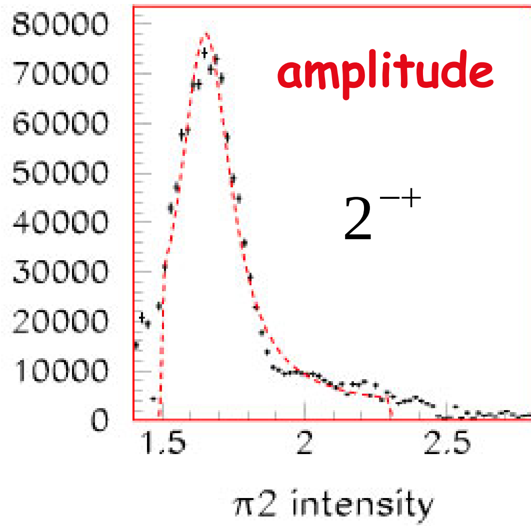
It is essential to understand the detector

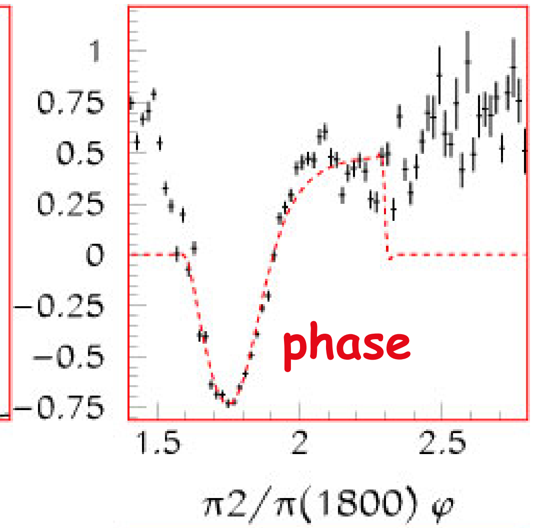
3π Studies

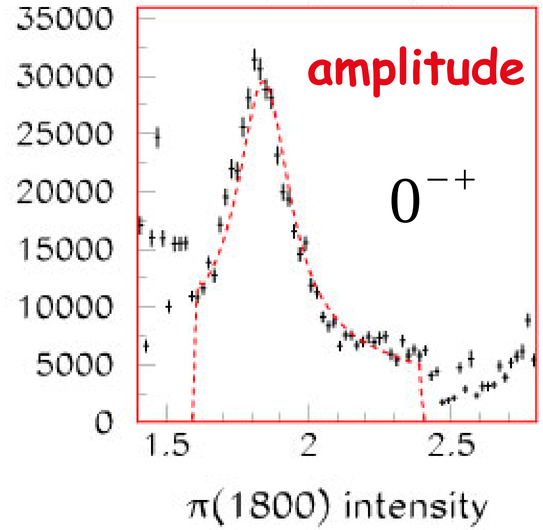
to continue with 10M event sample

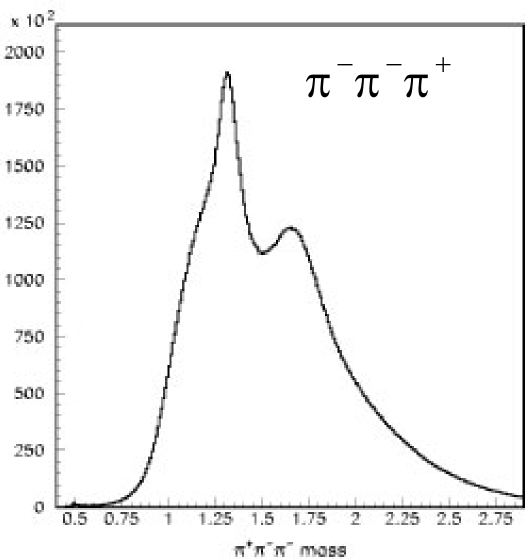
$$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$$

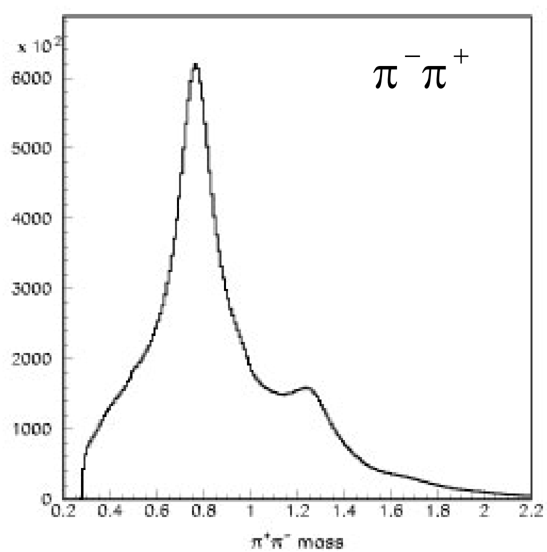
Sample results:











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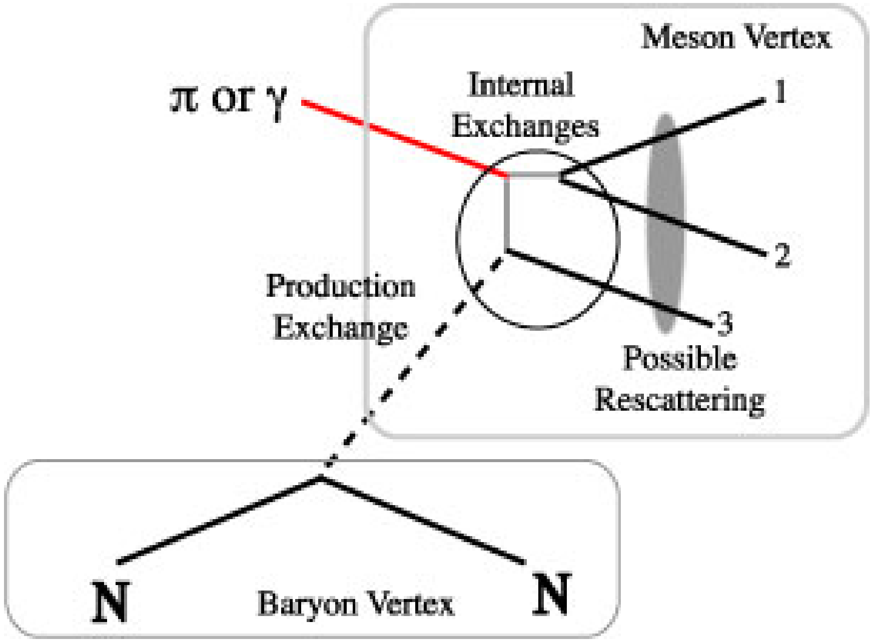
Physics Analysis Center

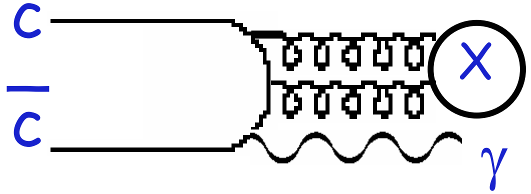
GlueX and CLEO-c (Cornell) are collaborating on proposals to DOE and NSF ITR to fund physics analysis center to solve common problems:

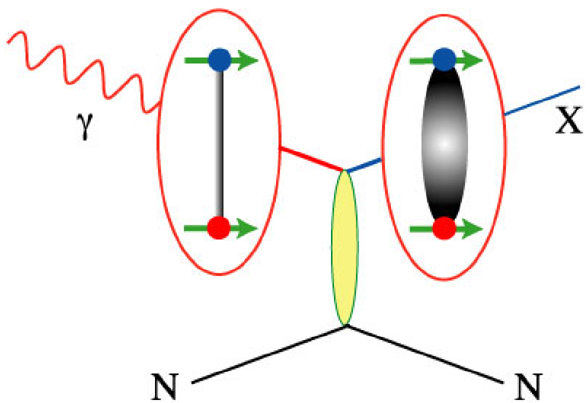
1. Large datasets
2. Understanding PWA

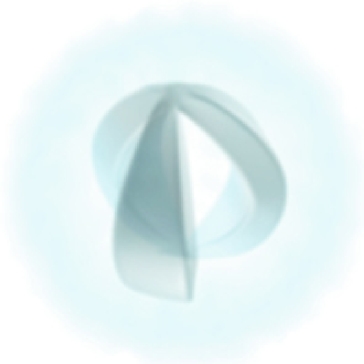
3π challenge an example



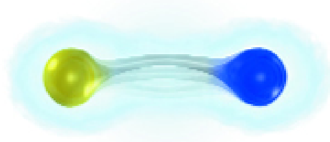
Complementarity







Glueballs
&
CLEO-c



Hybrids
&
Hall D
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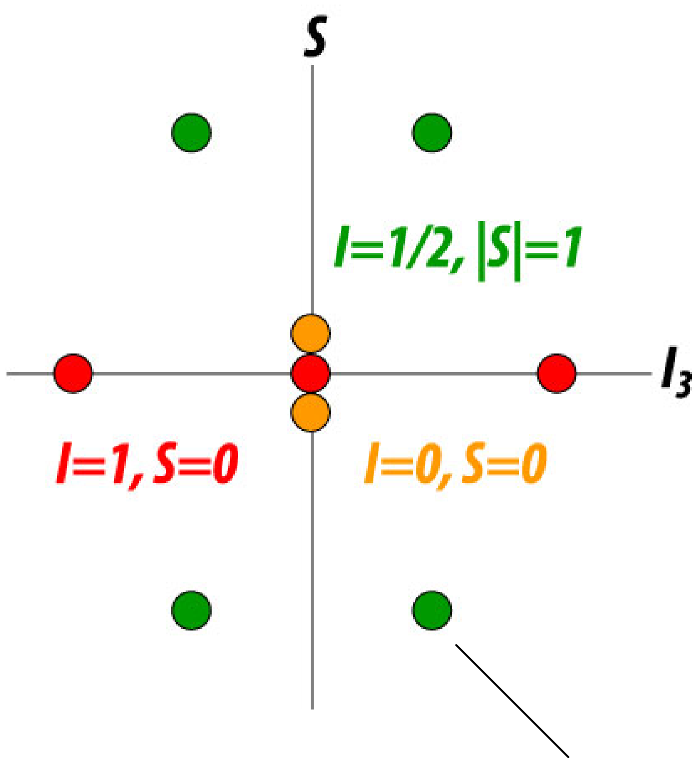
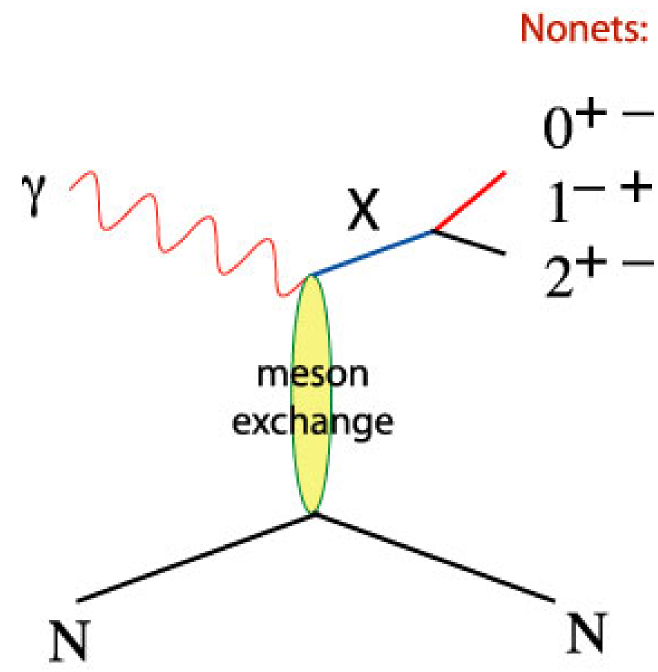
Goal: Map out Nonets



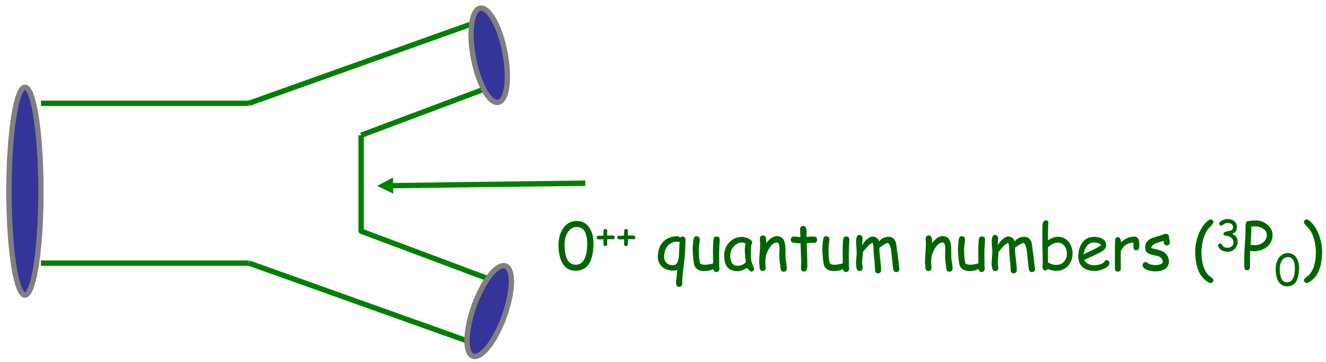
Note that |S| = 1 states do not have well-defined *C*



The candidate states have couplings to vector + meson

Decays of Hybrids

Decay calculations are model dependent - the $^3P_0$ describes normal meson decays.



The angular momentum in the flux tube stays in one of the daughter mesons (L=1) and (L=0) meson.

L=0: $\pi,\rho,\eta,\omega,\ldots$
L=1: a,b,h,f,...

$\eta\pi,\rho\pi,$ ... not preferred.

Strangeonium

$$\gamma \Leftrightarrow s\bar{s}$$

1. Mapping out the hybrid spectrum requires an understanding of normal mesons as well
2. Strangeonium is a bridge between lighter quark sector and charmonium
3. Only 5 strangeonium states are well-established.
4. In contrast to π and K beams, photoproduction will be particularly effective in producing strangeonium.

Strangeonium Decays

Known states:

$$\eta(540)\ \&\ \eta'(958)$$

$$\phi(1020)$$

$$f_2'(1525)$$

$$\phi(1680)$$

$$\phi_3(1854)$$

OZI-favored modes:

$$s\bar{s} \to \begin{cases} \phi\eta \\ \phi\eta' \\ \phi\phi \end{cases}$$

What is Needed?

Hermetic Detector:

- PWA requires that the entire event be kinematically identified - all particles detected, measured and identified. It is also important that there be sensitivity to a wide variety of decay channels to test theoretical predictions for decay modes.

  The detector should be hermetic for neutral and charged particles, with excellent resolution and particle identification capability. The way to achieve this is with a solenoidal-based detector.

Linearly Polarized, CW Photon Beam:

- Polarization is required by the PWA - linearly polarized photons are eigenstates of parity.
- CW beam minimizes detector deadtime, permitting dramatically higher rates

What Photon Beam Energy is Needed?

The mass reach of GlueX is up to about 2.5 GeV/c^2 so the photon energy must at least be 5.8 GeV. But the energy must be higher than this so that:

1. Mesons have enough boost so decay products are detected and measured with sufficient accuracy.
2. Line shape distortion for higher mass mesons is minimized.
3. Meson and baryon resonance regions are kinematically distinguishable.

But the photon energy should be low enough so that:

1. An all solenoidal geometry (ideal for hermeticity) can still measure decay products with sufficient accuracy.
2. Background processes are minimized.

⇒ 9 GeV photons ideal

What Electron Beam Characteristics Are Required?

Coherent bremsstrahlung will be used to produce photons with linear polarization so the electron energy must be high enough to allow for a sufficiently high degree of polarization - which drops as the energy of the photons approaches the electron energy.

⇒ **At least 12 GeV electrons**

In order to reduce incoherent bremsstrahlung background collimation will be employed using 20 µm thick diamond wafers as radiators.

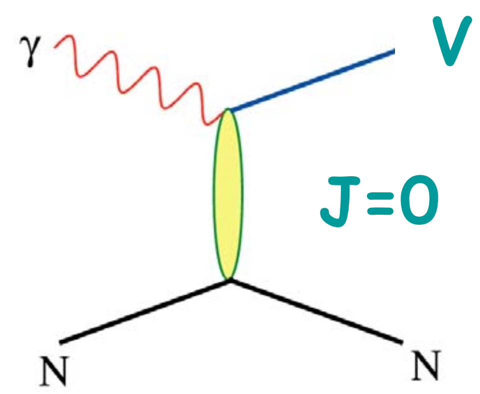
⇒ **Small spot size and superior emittance**

The detector must operate with minimum dead time

⇒ **Duty factor approaching 1 (CW Beam)**

Linear Polarization - I

Suppose we produce a vector via exchange of spin 0 particle and then $V \to SS$



photon V = vector

$|R\rangle$ m = 1 $Y_1^1(\theta,\phi) \propto \sin\theta \cdot e^{i\phi}$

$|L\rangle$ m = -1 $Y_1^{-1}(\theta,\phi) \propto \sin\theta \cdot e^{-i\phi}$

For circular polarization

$$W(\theta,\phi) \propto \sin^2\theta$$

For linear polarization

$$|x\rangle = \frac{|R\rangle + |L\rangle}{\sqrt{2}} \propto \sin\theta \cdot \cos\phi \qquad P_x:\ W(\theta,\phi) \propto \sin^2\theta \cdot \cos^2\phi$$

$$|y\rangle = -i\frac{|R\rangle - |L\rangle}{\sqrt{2}} \propto \sin\theta \cdot \sin\phi \qquad P_y:\ W(\theta,\phi) \propto \sin^2\theta \cdot \sin^2\phi$$

Loss in degree of polarization requires corresponding increase in stats

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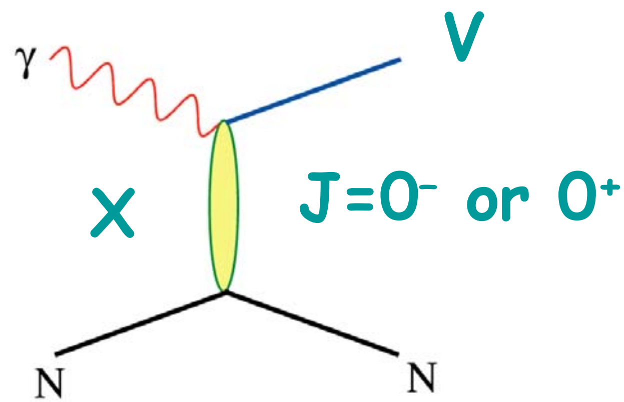
Linear Polarization - II



Center of Mass of V

for X, J = 0

photon X = exchange particle

$$L = 0,\ 1,\ \text{or}\ \ 2$$

$$P_V = P_\gamma \cdot P_X \cdot (-1)^L$$

Suppose we want to determine exchange: O^+ from 0^- or A^N from A^U

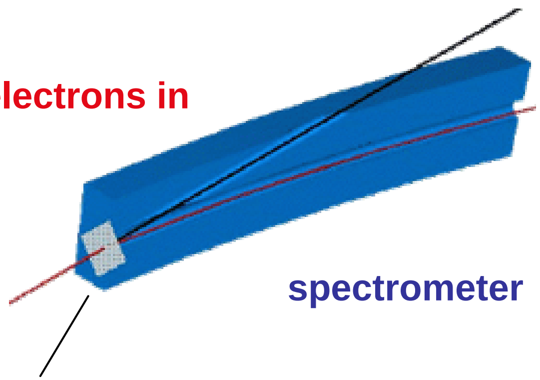
Parity conservation implies:

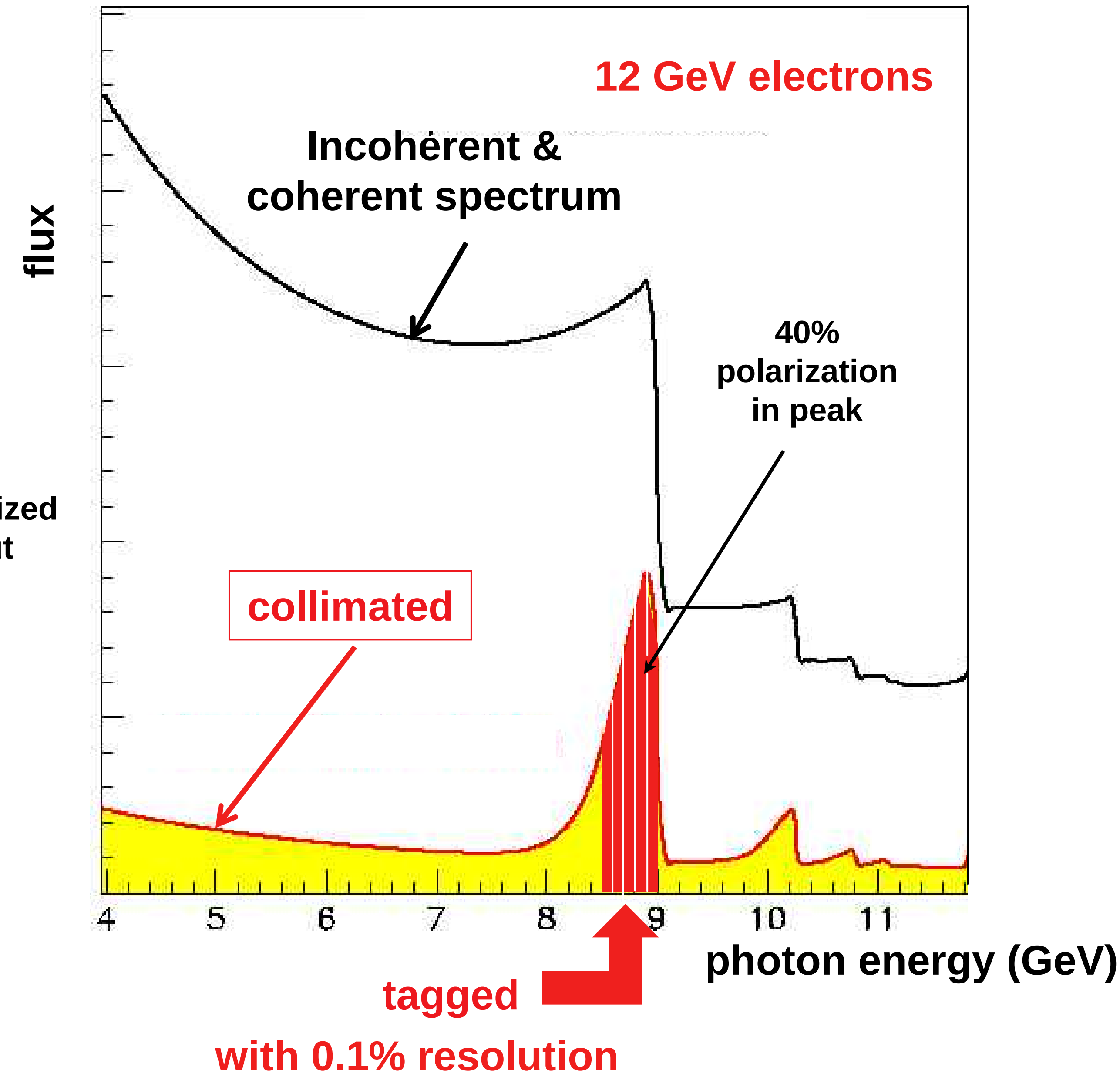
	photon		V = vector	
$\lvert R\rangle$	⇨	m = 1	⇨	$A^N + A^U$
$\lvert L\rangle$	⇦	m = -1	⇦	$A^N - A^U$

With linear polarization which is sum or diff of R and L we can separate
Linear Polarization Essential

Coherent Bremsstrahlung

This technique provides requisite energy, flux and polarization





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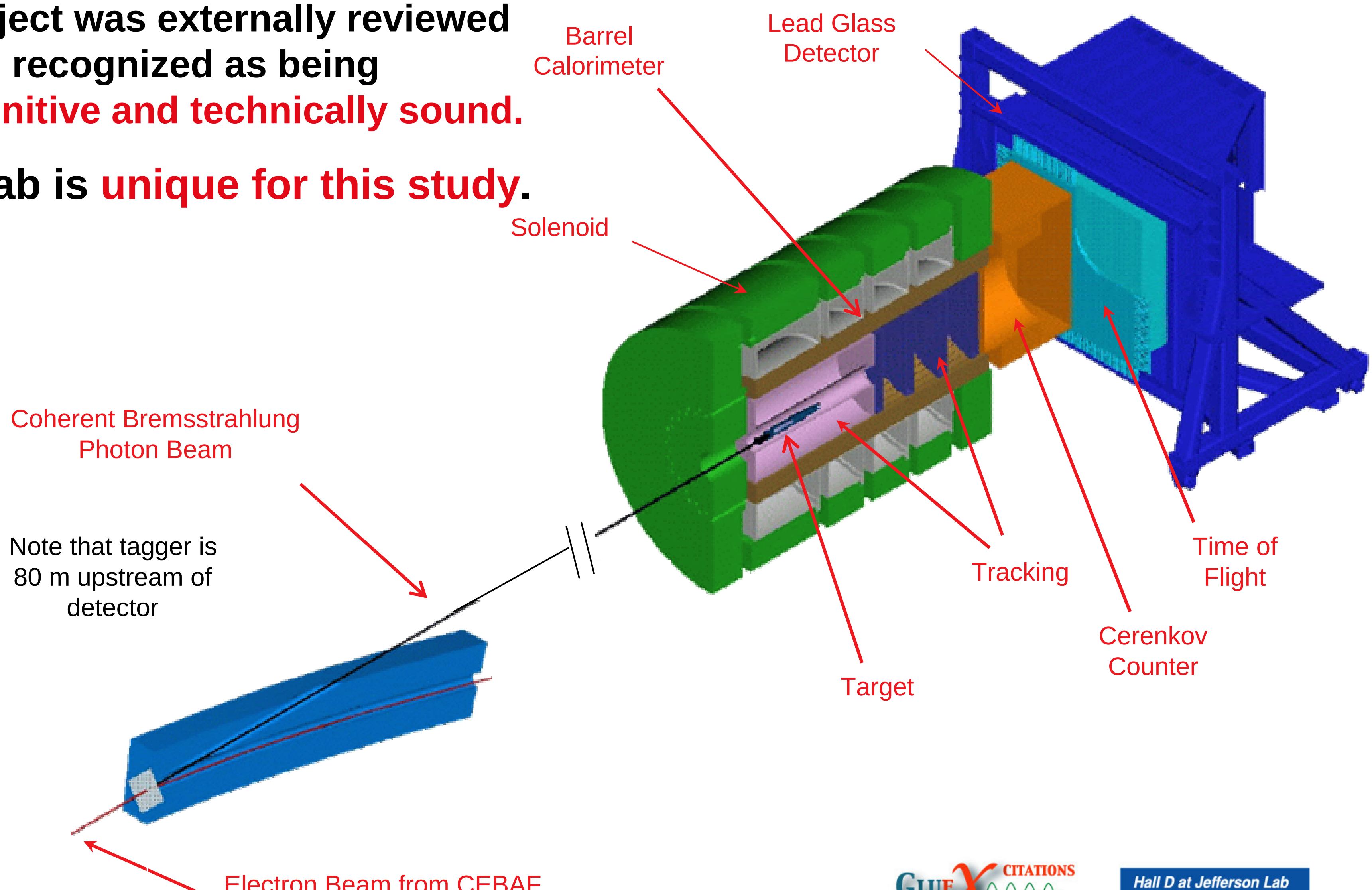
Detector

Project was externally reviewed and recognized as being definitive and technically sound.

JLab is unique for this study.



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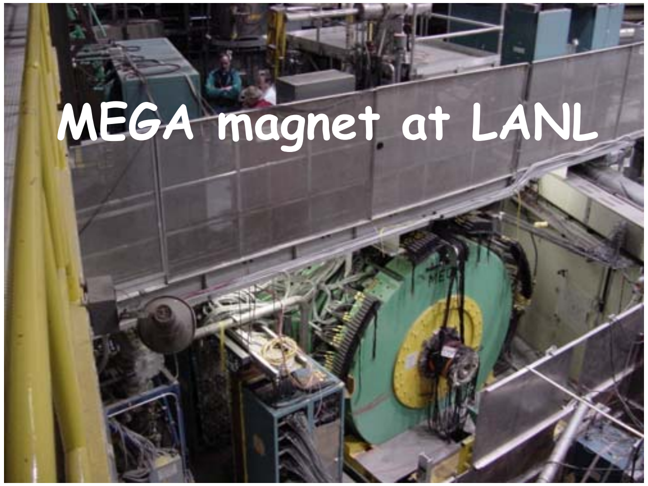
Solenoid & Lead Glass Array



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Computational Challenge

- GlueX will collect data at 100 MB/sec or 1 Petabyte/year - comparable to LHC-type experiments.

- GlueX will be able to make use of much of the infrastructure developed for the LHC including the multi-tier computer architecture and the seamless virtual data architecture of the Grid.

- To get the physics out of the data, GlueX relies entirely on an amplitude-based analysis - PWA – a challenge at the level necessary for GlueX. For example, visualization tools need to be designed and developed. Methods for fitting large data sets in parallel on processor farms need to be developed.

- Close collaboration with computer scientists has started and the collaboration is gaining experience with processor farms.

Experiment/Theory Collaboration

- From the very start of the GlueX collaboration, theorists have worked closely with experimentalists on the design of the experiment, analysis issues and plans for extracting and interpreting physics from the data.
- The PWA formalism is being developed with the goal of understanding how to minimize biases and systematic errors due to dynamical uncertainties - e.g. overlap of meson and baryon resonance production.
- Lattice QCD and model calculations of the hybrid spectrum and decay modes will guide the experimental search priorities. The Lattice QCD group computers at JLab should move into the 10 Teraflop/year regime by 2005 - in time to impact GlueX planning.

- INT (Seattle) will sponsor a joint workshop with JLab in early 2003 devoted to the physics of GlueX and a proposal for a 3-month program at INT in 2004 on GlueX physics has been submitted.

Testing the Capabilities of the GlueX Experiment Design

Double-blind Monte Carlo exercise

Starting assumption:

An exotic signal mixed in with 7 other states to mimic the BNL yield – a factor of 20 down from what is expected in photoproduction.

$$X(\text{exotic}) \rightarrow \rho\pi \rightarrow 3\pi$$

Mass

Input: 1600 MeV

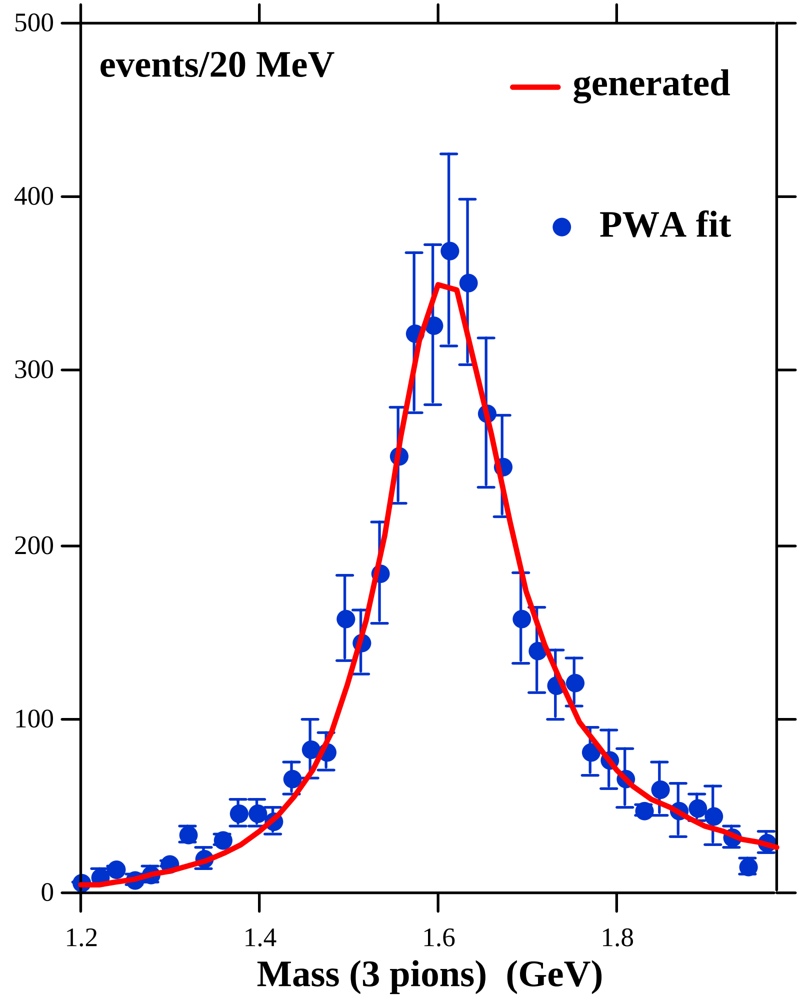
Output: 1598 +/- 3 MeV

Width

Input: 170 MeV

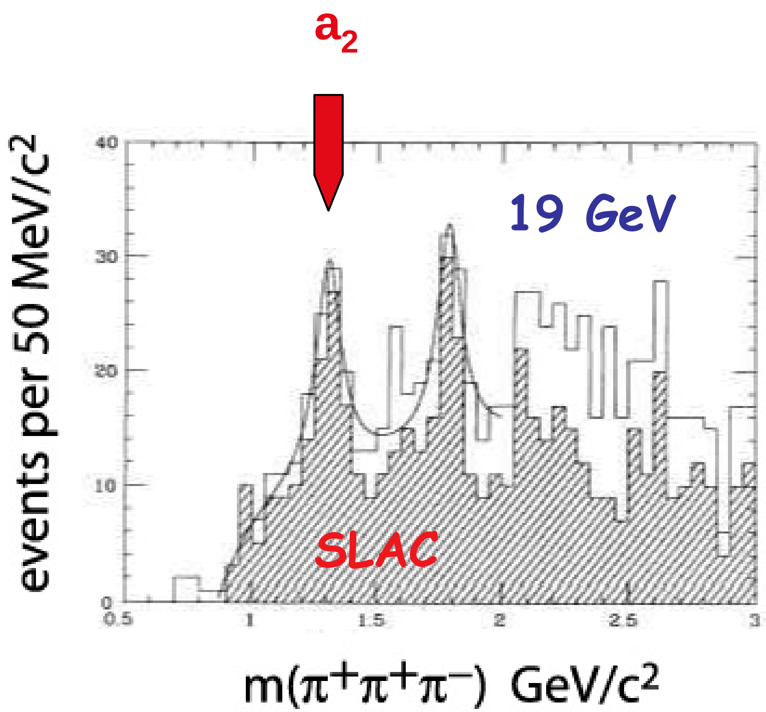
Output: 173 +/- 11 MeV

Even if the hybrids are produced at a rate well below expectation, we will see them easily

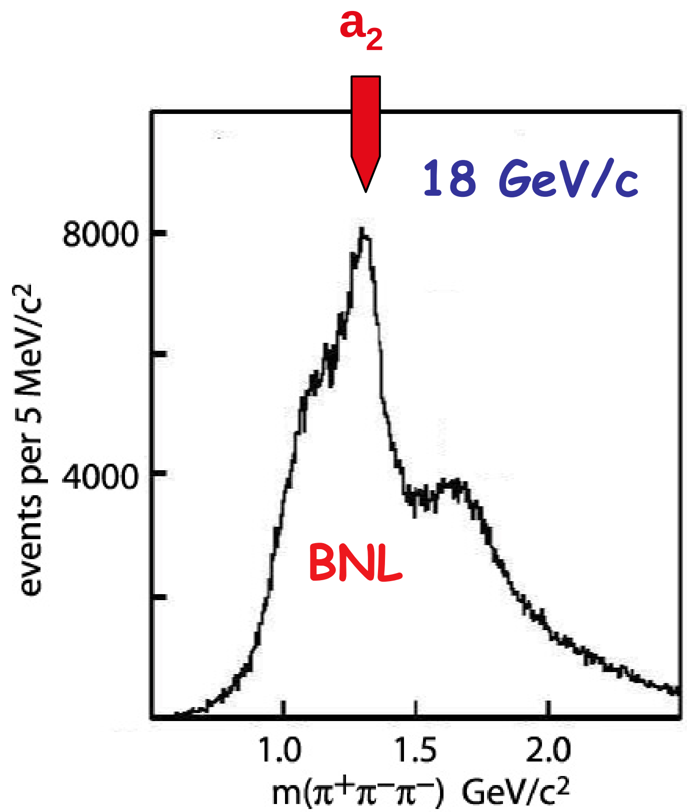


How GlueX Fares Compared to Existing Data

We will use for comparison – the yields for production of the well-established and understood a_2 meson



$$\gamma\, p \rightarrow \pi^{+}\pi^{+}\pi^{-} n$$



$$\pi^{-} p \rightarrow \pi^{+}\pi^{-}\pi^{-} p$$

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How GlueX Fares Compared to Existing Data

We will use for comparison – the yields for production of the well-established and understood a_2 meson

Experiment	a_2 yield	Exotic Yield
SLAC	10^2	--
BNL (published)	10^4	250
BNL (in hand - to be analyzed)	10^5	2500
GlueX	10^7	$5x\ 10^6$

More than 10^4 increase

GlueX estimates are based on 1 year of low intensity running (10^7 photons/sec)

Even if the exotics were produced at the suppressed rates measured in π-production, we would have 250,000 exotic mesons in 1 year, and be able to carry out a full program of hybrid meson spectroscopy

Conclusions

- An outstanding and fundamental question is the nature of confinement of quarks and gluons in QCD.
- Lattice QCD and phenomenology strongly indicate that the gluonic field between quarks forms flux-tubes and that these are responsible for confinement.
- The excitation of the gluonic field leads to an entirely new spectrum of mesons and their properties are predicted by lattice QCD.
- But data are needed to validate these predictions.
- Only now are the tools in place to carry out the definitive experiment and JLab – with the energy upgrade – is unique for this search.
- And the GlueX Detector will be a versatile tool for all meson production and decay studies - an electronic bubble chamber.